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On periodic behavior of weakly turbulent premixed flame corrugations

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ABSTRACT

Periodicity in evolution of premixed methane–air V-shaped flames in the space domain is investigated experimentally. The experiments were performed using the Mie scattering and Particle Image Velocimetry techniques. Three Reynolds numbers of 510, 790, and 1057 along with two fuel–air equivalence ratios of 0.6 and 0.7 were tested in the experiments. The analyses were performed using the Proper Orthogonal Decomposition (POD) technique for the flame front position as well as the velocity data pertaining to non-reacting flow condition. The POD analysis shows that the spectral characteristics of the mode shapes associated with the velocity and the flame front position data feature similarities; however, the corresponding temporal coefficients are significantly different. Specifically, the POD mode shapes pertaining to both velocity and flame front position data feature dominant instabilities. It was shown that the normalized wave number pertaining to these instabilities are similar and equal to the Strouhal number corresponding to non-reacting flow over a circular cylinder. Comparison of the normalized temporal coefficients show that, for the flame front position data, the normalized first and second coefficients are mainly centered close to the origin; however, those associated with the velocity data are positioned around a unity radius circle. This was argued to be linked to the ratio of the corresponding first and second eigenvalues. Specifically, it was shown that, as this ratio approached to unity, the signal energy becomes distributed between the first and the second POD modes. As a result, the normalized temporal coefficients follow a circular pattern.

1. Introduction

Several engineering equipment, for example, stationary gas turbines, lean premixed and pre-vaporized jet engines, and spark ignition engines operate under the mode of turbulent premixed combustion [1–3]. Thus, studying this mode of combustion is of significant importance; and, as a result, numerous laboratory settings have been developed to investigate turbulent premixed flames, see, for example, the review papers [3–5]. These studies show that several flame configurations, e.g., V-shaped, Bunsen-type, swirl-stabilized, spherical, and stagnation, have been utilized to study turbulent premixed flames [3–5]. The flame configuration used in the present study is V-shaped. Previous investigations associated with the V-shaped flames, e.g., [6–8], show that the turbulence intensity (u_{RMS}/U) strongly influences the characteristics of the flame front, where u_{RMS} and U are the root-mean-square (RMS) of velocity fluctuations and the mean velocity in the reactants region, respectively. For relatively small values of the turbulence intensity, i.e., $u_{\mathrm{RMS}}/U \lesssim 0.06$, observations reported in Shanbhogue [9], Petersen and Emmons [10], and Kheirkhah and Gülder [8] indicate that the flame front corrugations are periodic and symmetric in the space domain. To the best knowledge of the authors, details associated with these characteristics are yet to be investigated. Since the flame-holder utilized in the present investigation has a circular cross section, a brief review of non-reacting flow development over circular cylinders is presented. Then, findings of past studies associated with the effect of heat release on the flow development are reviewed.

Several investigations have been performed in the past decades to study the development of isothermal flow over circular cylinders, see, for example, the review papers by Berger and Wille [11], Bearman [12], Choi et al. [13], and Williamson [14]. These investigations [11–14] show that the flow development is strongly affected by the Reynolds number estimated based on the diameter of the cylinder (Re_d). For $Re_d \lesssim 5$, the flow is attached to the surface of the cylinder, and the corresponding flow regime is called the creeping flow [15]. For $5 \lesssim Re_d \lesssim 50$, the flow is composed of two steady recirculation zones behind the cylinder, and the pertaining flow regime is referred to as the laminar steady regime [14,15]. Results provided in Zdravkovich [15] show that, for $50 \lesssim Re_d \lesssim 200$,

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Nomenclature

a_j^i	The jth temporal coefficient for reconstruction of the PIV data associated with the ith image
b_j^i	The jth temporal coefficient for reconstruction of the ith flame front signal
d	Flame-holder diameter
d_p	Seed particle diameter
D	Nozzle inner diameter
$\mathcal{D}$	Mass diffusivity
f_v	Vortex shedding frequency
$\boldsymbol{G}^i$	The ith eigenvector of the flame front data
$\boldsymbol{H}^i$	The ith eigenvector of the velocity data
I	The imaginary unit, $\sqrt{-1}$
K	The total number of data in the velocity field, i.e., 128×128
Ka	The Karlovitz number
l^*	The normalized vertical distance between two local maximums/minimums of the first and the second mode shapes of the velocity data
Le	Lewis number
M	The number of data points associated with the flame front position signal
n	The direction normal to the flame front
N	The number of PIV images, i.e., 1000
$\boldsymbol{p}^i$	The matrix of streamwise and transverse velocity fluctuations associated with the ith PIV image
P	Gas pressure
$\boldsymbol{P}$	The matrix of velocity fluctuations made from $\boldsymbol{p}^i$
Pr	Prandtl number
$\boldsymbol{Q}$	The autocovariance martix of $\boldsymbol{P}$
$r(y)$	the complex function constructed from the flame front position signal and the corresponding Hilbert transform
$\boldsymbol{R}$	The matrix constructed from $\boldsymbol{x}'^i$, $\boldsymbol{R} = [\boldsymbol{x}^1, \boldsymbol{x}^2\ \boldsymbol{x}^3, \ldots, \boldsymbol{x}^N]$
Re_d	The Reynolds number estimated based on the diameter of the flame-holder
$\boldsymbol{S}$	Autocovariance matrix of $\boldsymbol{R}$
S_{L0}	The un-stretched laminar flame speed
St	The Strouhal number
T	Gas temperature
$T_{\mathrm{b,\,u}}$	Burnt and unburnt gas temperature, respectively
$\overline{u}, \overline{v}$	Mean streamwise and transverse velocity, respectively
u', v'	Streamwise and transverse velocity fluctuations
u_{RMS}	RMS of the streamwise velocity fluctuations pertaining to non-reacting flow condition
U	Mean bulk flow velocity
$\overrightarrow{V}$	The velocity vector
x, y, z	Axes of the coordinate system shown in Fig. 1(b)
$\overline{x}, x_{\mathrm{RMS}}$	Mean and root-mean-square of the flame front position
$x'_{\mathrm{l,r}}$	The flame front position fluctuations associated with the left and right wings, respectively
x'^i	The ith matrix of the velocity fluctuations
α	Phase of the flame front position signal
γ^i	The ith eigenvalue associated with the velocity fluctuations
γ_t	The threshold eigenvalue associated with the velocity fluctuations
ϵ	The error associated with estimation of the velocity data
ϵ_i	The inner cut-off length scale
δ_L	Laminar flame thickness
$\boldsymbol{\eta}$	The matrix of the mode shapes utilized for reconstruction of the velocity data
$\boldsymbol{\theta}^i$	The ith normalized POD mode shape associated with the velocity data
κ_c	The critical wavenumber
λ^i	The ith eigenvalue of the flame front position data
Λ	Integral length scale
ν	Gas kinetic viscosity
ρ	Gas density
ρ_u	Unburnt gas density
τ	Time utilized for the statistical analyses $0 \le \tau \le t$
ϕ	Fuel–air equivalence ratio
$\boldsymbol{\psi}^i$	The ith normalized mode shape of the flame front position
$\overrightarrow{\omega}, \omega_z$	Vorticity vector and the z-component of the vector, respectively

which is known as the laminar vortex shedding regime [14], a global instability develops in the wake of the cylinder. This instability leads to periodic formation and shedding of vortical flow-structures in the wake of the circular cylinder, known as von Kármán vortex street. The vortex shedding frequency (f_v) can be obtained from the following equation [15,16]:

$$St = \frac{f_\mathrm{v} d}{U}, \tag{1}$$

where St is referred to as the Strouhal number. For the laminar vortex shedding regime, the Strouhal number increases from approximately 0.12 to 0.19 by increasing the Reynolds number from about 50 to 200 [15,16]. For $200 \lesssim Re_d \lesssim 400$, transition to turbulence occurs in the wake of the cylinder, and the corresponding regime is referred to as the wake transition regime [15]. In this regime, the Strouhal number (St) varies between approximately 0.19 and 0.21. For $400 \lesssim Re_d \lesssim 10^5$, transition to turbulence occurs in the shear layers developed on both sides of the cylinder [15,17]; and the corresponding regime is referred to as the shear layer transition regime [14]. In this regime, the Strouhal number is approximately 0.21. For Reynolds numbers beyond 10^5, the transition to turbulence takes place in the boundary layers developed on both sides of the cylinder, and the corresponding regime is referred to as the boundary layer transition regime [18,19]. The Strouhal number associated with the boundary layer transition regime varies between about 0.2 and 0.5 [15,18,19]. Further details associated with isothermal flow development over circular cylinders can be found in Zdravkovich [15].

Previous studies show that the combustion heat release influences the flow development over circular cylinders [20–26]. This influence can be elaborated using the vorticity transport equation [20], given by:

$$\frac{\mathrm{D}\overrightarrow{\omega}}{\mathrm{D}t} = (\overrightarrow{\omega} \cdot \overrightarrow{\nabla})\overrightarrow{V} + \nu\nabla^2\overrightarrow{\omega} + \frac{\overrightarrow{\nabla}\rho \times \overrightarrow{\nabla}P}{\rho^2} - \overrightarrow{\omega}(\overrightarrow{\nabla} \cdot \overrightarrow{V}). \tag{2}$$

In Eq. (2), $\overrightarrow{\omega}$, $\overrightarrow{V}$, ν, ρ, and P refer to vorticity vector, velocity vector, kinematic viscosity, fluid density, and pressure, respectively. The term on the left-hand-side (LHS) of Eq. (2) is the total derivative of the vorticity vector. The first term on the right-hand-side (RHS) is referred to as the vortex stretching and is related to the normal strain in the direction of the vorticity vector. This strain results in narrowing of the vortex tubes, and, as a result, increasing the vorticity values. The second term on the RHS of Eq. (2) is the